

circuit potential, which is near -700 mV (SCE) or -770 mV (Cu/CuSO₄) for the environments in question.

No pronounced effect of temperature on the kinetics of near-neutral pH SCC has been observed, but the research into temperature effects has been very limited. Parkins, et al. (1994) conducted a series of SSRTs at temperatures between 10 and 45°C. As is shown in Figure A-8, the considerable scatter in the data probably would mask any temperature effect that might exist. Based upon the fact that near-neutral pH stress-corrosion cracks frequently have been found far downstream from compressor stations, some people have concluded that temperature is not important. However, the fact that the most severe SCC (that leading to service failures) usually has been near the discharge of compressor stations (NEB 1996) raises some question about that conclusion.

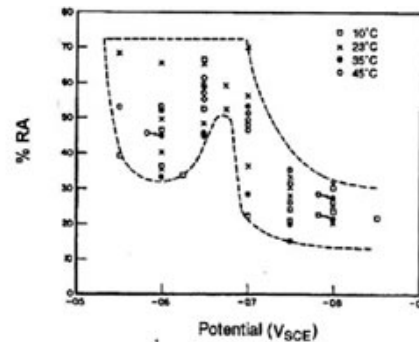


Figure A-13-8 Effect of Temperature on Reduction in Area for an X65 Steel Subjected to Slow-Strain-Rate Tests in NS4 Solution with pH about 6.4

From a mechanistic viewpoint, arguments could be made either way regarding an effect of temperature, depending upon the relative roles of dissolution and hydrogen. As with most chemical reactions, the rate of dissolution would be expected to increase exponentially with increasing temperature. However, the corrosivity of the environment is strongly affected by CO₂, the solubility of which decreases with increasing temperatures. The temperature dependence of hydrogen embrittlement for line-pipe steels is not known, but studies on quenched-and-tempered steels (Tyson 1979) have shown a maximum effect around -100°C , the effect becoming very small above room temperature (see Figure A-9).

Stress. As is the case for high pH SCC, the role of stress appears to be to produce some continual plastic deformation at the crack tip, which also seems to be required for near-neutral pH SCC. Although Zhang, et al. (1999) reported near-neutral pH SCC under static loads, most researchers have found it useful, if not necessary, to vary the stress during the test to promote some continual deformation.

Steel. No obvious relationships between susceptibility to near-neutral pH SCC and the grade, composition, or microstructure of the steel have been apparent from analyses of pipe that developed SCC in service (Dupuis 1998). However, several recent laboratory studies of various batches of steel with different microstructures have suggested that steels with more uniform microstructures may be less susceptible to near-neutral pH SCC (Meyer, et al. 2003). Those results are based upon a very small sampling of steels, so more research in this area would be useful.

Recent studies showing a correlation between residual stresses and locations of SCC on a given joint of pipe (Beavers, Johnson and Sutherby 2000) and between pipe manufacturers and probability of finding SCC in the field (Beavers and Harper 2004) suggest that residual stresses from the manufacturing process may be very important.

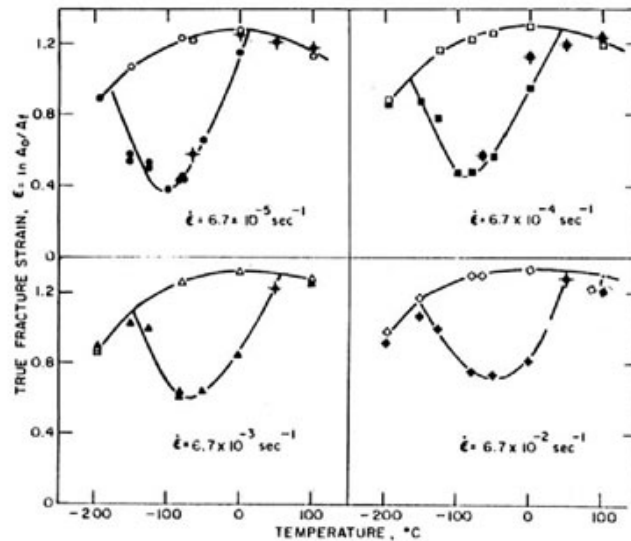


Figure A-13-9 Effect of Temperature on Hydrogen Embrittlement of a Quenched-and-Tempered Steel with a Yield Strength of About 100 Ksi

(Note: Solid points represent hydrogen-charged specimens.)

A.2.3 Summary of Gaps Related to Causes of SCC

Environment. Although the NS4 solution or something similar is being used by most researchers to simulate the environment that causes near-neutral pH SCC in the field, many researchers have experienced difficulties in initiating SCC in that environment under realistic loading conditions and in obtaining reproducible results in terms of crack growth rates. There have been several reports of unexpected and unexplained very high or very low growth rates. One possible explanation is that there are yet some undiscovered constituents in the field environment that may be critical in terms of SCC initiation and growth.

A fundamental understanding of how the environment at the steel surface under a disbonded coating relates to the surrounding soil and other external factors also has not been fully developed.

Stress. Many research projects have shown that low-amplitude pressure (stress) fluctuations and high-amplitude fluctuations can affect the growth of both high pH and near-neutral pH stress-corrosion cracks. However, it is not clear what kinds of pressure fluctuations (amplitude, frequency,

and mean stress) are most harmful or how those factors might be related to the properties of the steel.

Steel. Although there can be large variations in susceptibility of different batches of steel to SCC, even within a single grade, it is not yet possible to predict the susceptibility from the composition and microstructure, nor is it possible to design a steel that will be resistant to SCC. Work completed by CEPA demonstrated that residual stresses in the pipe, probably as a result of the pipe manufacturing process, can have a significant impact on SCC susceptibility (Beavers, Johnson and Sutherby 2000).

A.3 Methods for Managing SCC

It is highly unlikely that any single approach to managing SCC will be optimum for all pipeline companies. The choice of one or more approaches will depend on specific characteristics of a pipeline such as the following:

- Is it an existing line or a future one being designed
- Is the more likely threat from high pH SCC or near-neutral pH SCC
- Is the line piggable in its current condition
- What are the feasibility and cost of hydrostatic retesting (as affected by factors such as water supply or disposal, elevation differences, etc.)
- What are the economics of aftercooling gas prior to injection into a pipeline
- What is the ability to control cathodic protection (as affected by factors such as soil resistivity, accessibility, and coating condition)

Following is a list of options that a pipeline company might consider for managing SCC on its system:

Existing pipelines:

- Locate SCC and treat the pipe
 - ⇒ Locate
 - Bell-hole inspections
 - Hydrostatic testing
 - ILI
 - ⇒ Evaluate/size the cracks
 - Buffing/grinding
 - Non-destructive evaluation (NDE)
 - ⇒ Treat
 - Buffing/grinding
 - Sleeving
 - Remove the joint
 - Leave cracks and establish safe re-inspection interval

- Change operating practices
 - ⇒ Lower temperature (for high pH SCC)
 - ⇒ Eliminate harmful pressure fluctuations
 - ⇒ Improve cathodic protection

Additional options for future pipelines:

- Select effective coating
- Consider steel susceptibility
- Optimize operating conditions
 - ⇒ Temperature
 - ⇒ Stress
 - ⇒ Pressure fluctuations
 - ⇒ Cathodic protection

Table A.1 and Table A.2 summarize some of the most important questions that remain regarding each of the options for managing SCC and the research areas that could be pursued to answer those questions.

Table A.1 Questions and Research Areas Relevant to Existing Pipelines

Management Technique	Question	Research Area
Locate and Treat SCC		
Locate SCC	How to increase the effectiveness and reduce the cost by identifying high-probability areas for focusing efforts	Develop improved site-selection models
	How to establish suitable inspection intervals	Develop improved crack-growth models
	How to reduce the cost of ILI for gas pipelines	Develop new ILI techniques that do not require a liquid couplant
Evaluate/size cracks in the ditch	How to obtain accurate measurements with portable equipment	Develop new in-the-ditch sizing technologies
Leave small cracks and establish safe re-inspection interval	How to ensure that interval is short enough to prevent unacceptable amount of growth but not too short as to be unnecessarily expensive	Develop improved crack-growth models
Change Operating Practices		
Lower temperature	Does temperature really have no significant effect on near-neutral pH SCC	Investigate effect of temperature on initiation and growth rates
Eliminate harmful pressure fluctuations	What kinds of pressure fluctuations are most harmful	Develop improved crack-growth models
Improve cathodic protection	Reasonably well understood	None needed

TableA.2 Additional Questions and Research Areas Relevant to Future Pipelines

Management Technique	Question	Research Area
Steel Susceptibility	How does SCC susceptibility depend upon composition, processing, and properties of steel	Empirical comparison of various batches of steel and regression analysis
		Fundamental study to relate susceptibility to properties, composition, and processing
Select effective coating	Are coatings with good service histories prone to failure after longer times	Monitor field-failure experience
Optimize operating conditions	Same as for existing pipelines	Same as for existing pipelines

The following sections describe the current level of understanding and possible future research approaches for each of the research areas listed in Table A.1 and Table A.2.

A.3.1 Site-Selection Models

Very soon after the initial discovery of SCC in pipelines, data collected suggested that the locations of significant SCC were "... strongly related to terrain conditions surrounding the pipe where there was the potential for pipe coatings to have disbanded" (NEB 1996). If SCC is discovered in some location due to a failure, visual inspection, or non-destructive inspection, there is a high probability that SCC can be found in other joints of pipe in the same vicinity. This has led to a continued effort to find ways to predict locations where SCC may be highly likely or other locations where it may be highly unlikely or even impossible. The obvious benefits of such an ability would be to allow pipeline companies to focus their remedial efforts where they would be most effective and not waste time and money in areas where there is no significant threat of SCC.

It should be noted that site-selection models might take different forms from system to system since factors that may be highly significant on one system might be completely absent from another. For example, while recent work reported in "*Stress Corrosion Cracking Prediction Model*" (Beavers and Harper 2004) demonstrated that the pipe manufacturer was highly statistically significant in the SCC prediction model for one pipeline company, pipe manufacturer might not be highly statistically significant for other companies.

Site-Selection Models for High pH SCC. Based upon statistics of reported incidents of high pH SCC, two models have been proposed to prioritize or rank areas in terms of relative probability of high pH SCC – one by Martinez and Stafford (1994) and the second by Eiber (1998).

Both models consider soil moisture level, coating condition, operating stress, cathodic-protection level, and gas temperature. The Martinez model also considers soil pH, coating age, pipe age, history of SCC leaks and ruptures, and length of time since the most recent hydrostatic retest or bell-hole examination. The Eiber model also considers coating type, clay content of the soil, pipe surface preparation, and magnitude of stress fluctuations. The Eiber model requires less specific knowledge of the conditions at the surface of the pipe.

The Martinez model assigns either zero or one point for each condition and adds the points to get a relative probability. The Eiber model assigns weights to each factor to represent the estimated relative importance and then adds the values.

Both models represent thoughtful, prudent approaches to prioritizing areas for attention with respect to high pH SCC, especially in view of the limited amount of data upon which they could be based and against which they could be judged. Both give relatively high values for known locations of SCC.

However, as more data are collected from the field and a better understanding is gained in the laboratory, there may be several ways in which the models could be modified to make them more reliable:

- When reliable ILI information becomes available, the models could be tested against areas where SCC has not occurred in addition to more areas where it has.
- The weighting factors might then be refined to improve the reliability.
- When dealing with independent factors that affect the probability of an event, the probabilities of the individual factors usually are multiplied together, not added. Some system of multiplying ratings in the models should be considered.
- Although extensive early studies of the soils and geological features that were associated with high pH SCC failures revealed no correlation with chemistry, (Mercer 1979) more recent work by Beavers suggests that soils with high amounts of sodium or potassium would favor high pH SCC because they would allow highly concentrated solutions of carbonates and bicarbonates to be produced (Beavers and Durr 2001). Conversely, high amounts of calcium or magnesium would lower the solubility of carbonates and bicarbonates to very low levels.

Site-Selection Models for Near-neutral pH SCC. In contrast with the site-selection models for high pH SCC, the models for near-neutral pH SCC have been based more on characteristics of the soil and terrain with less emphasis on operating history and other factors.

A limited survey of the industry indicated mixed experience with respect to success rate. As is shown in Table A.3, success rates in terms of correct positive indications for the tape-coated pipe ranged from 12 percent to 80 percent. For a coal-tar-coated line, there were no correct positives in a small number of digs.

Table A.3 Success Rates of Site-Selection Models for Near-Neutral pH SCC

Type Coating	No. of Digs	Correct Positive	Correct Negative	False Positive	False Negative	Comments
Tape	>800	80 percent	?	20%	?	A
Tape	85	12%	54%	18%	16%	
Tape	>100	40%	?	60%	?	B
Coal Tar	7	0	0	100%	0	
A. Tenting at longitudinal double-submerged arc weld.						
B. Minor SCC; no "significant" cracks. Similar statistics for random digs.						

A more recent study on a U.S. gas pipeline found a significant correlation between locations of SCC and a combination of coating type, soil type, and pipe manufacturer, the latter correlation speculated to be related to residual stresses (Beavers and Harper 2004).

There are a number of reasons why it is difficult to evaluate site-selection models for near-neutral pH SCC:

- They are based on correlating field experiences rather than a fundamental understanding of how the soil and geology contribute to the conditions that promote cracking. Thus, the models tend to improve over time because more data are accumulated, so the reliability this year might be much better than it was several years ago.
- They generally have been based on proprietary data and algorithms.
- They appear to be geographically specific. For example, the algorithms that work for Eastern Canada do not necessarily work for Western Canada.
- There are interdependent factors associated with locations of near-neutral pH SCC. For example, SCC on tape-coated pipe has a tendency to occur more often in poorly drained soils, while SCC on asphalt-coated pipe tends to occur in well-drained soils (CEPA 1998). However, there are exceptions to that rule of thumb as well; for one tape-coated liquid line in Western Canada, the cracking was more frequent and deeper where the soil was well drained (Krishnamurthy et al. 2000). Not surprisingly, algorithms that work for tape-coated pipe do not work well for asphalt-coated pipe.

Research Gaps Related to Site-Selection Models. Although several important projects currently are being conducted to correlate various soil characteristics with the locations of SCC, there are several other opportunities to improve existing models:

- From the soil extracts that produced exceptionally high or low crack growth rates of near-neutral pH SCC, attempt to identify the critical constituents. Identifying the accelerating constituent would have the added benefit of allowing laboratory tests to be conducted in much shorter times, thus producing more data per dollar.
- As more ILI runs are completed, test the parameters of the pipe and geology from places where SCC is not found against the models. It also may be useful to compare parameters related to large cracks versus shallow cracks.
- Incorporate more operating data into models for near-neutral pH SCC and more soils/geology data into models for high pH SCC. This may include considerations for topographical depression correlation with SCC, and additional data and correlations for SCC occurrence proximate to compressor stations.
- Develop a fundamental mechanistic model for the relationship between the nature of the environment at the pipe and factors such as soil chemistry, soil resistivity, cathodic-protection values, moisture levels, and coating conditions, rather than relying solely on empirical correlations. The model should be able to predict different areas where either high pH SCC or near-neutral pH SCC is more probable.

A.3.2 Crack-Growth Models

Ability to predict crack growth rates is important to predicting remaining life, assessing risk, determining what kinds of operating practices (such as pressure fluctuations) are harmful or beneficial, and establishing reasonable intervals for hydrostatic retesting or ILI. B31.8S states “When time-dependent anomalies such as ... stress corrosion cracking are being evaluated, an analysis using appropriate assumptions about growth rates shall be used to assure that the defect will not attain critical dimensions prior to the scheduled repair or next inspection.” It further states that, if an SCC failure has occurred, the pipeline company must have a documented hydrostatic retest program with a technically justified retest interval.

Models of High pH SCC Growth Kinetics. A four-stage model of high pH SCC that was proposed by Parkins (1988) is illustrated in Figure A-10. Stage 1 represents the time required to deteriorate the coating and build up the necessary environmental conditions for SCC. It probably is the least predictable stage, and it probably varies by several orders of magnitude from one pipeline to another depending upon the condition of the coating, the nature of the backfill, and many other factors. If a crack-growth model is used to estimate the remaining life of a pipeline that is known to contain stress-corrosion cracks, then knowledge of Stage 1 is irrelevant. However, if one is trying to predict the total life of a pipeline, then it will be necessary to make an arbitrary assumption about the length of Stage 1.

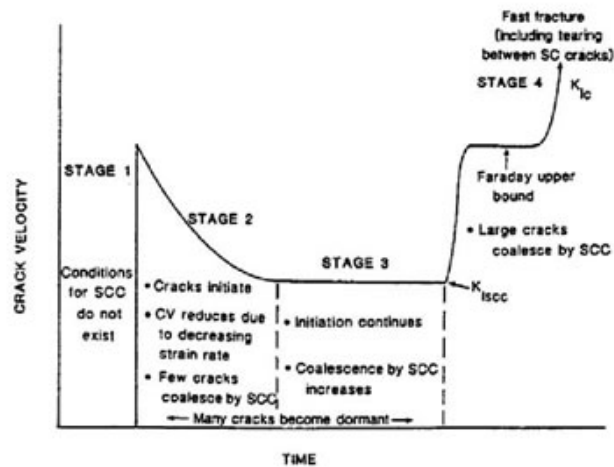


Figure A-13-10 Four-Stage Model of High pH SCC

The final event in Stage 1 is the initiation of a stress-corrosion crack. Parkins has shown evidence that the initiation mechanism is simply selective dissolution of the grain boundaries, which is the same mechanism as that for crack growth (Parkins 1994).

Stage 2 represents the exponential decrease in crack growth rate with time and may cover only a few days for an individual crack. The schematic illustration in Figure 9.10 greatly exaggerates the length of Stage 2.

Stage 4 represents the final part of the growth process where the crack is so large that a small amount of growth reduces the remaining wall thickness enough to cause the driving force to increase fast enough to overcome the effect of work hardening. Parkins has shown that the growth rate in Stage 4 can be calculated from Faraday's Law and the corrosion rate as measured from a polarization curve (Leis and Parkins 1998). For the carbonate/bicarbonate environment at 75°C, it typically is around 2×10^{-6} mm/sec. Stage 4 is followed by rapid mechanical penetration of the pipe wall to produce a leak or rupture. Both Parkins (2000) and Leis (1995) have argued convincingly that the time spent in Stage 4 is a relatively small fraction of the total time to failure.

The key to predicting the remaining life of a pipe with small stress-corrosion cracks lies with Stage 3, which probably involves sporadic crack growth due either to crack coalescence or cyclic softening or both.

In laboratory experiments, average crack growth rates typically are calculated by measuring the crack depth at the end of the test and dividing by the total test time. Since it is known that cracks initiate continuously during a test, (Parkins 1988) the deepest crack usually is used for reporting a maximum average growth rate.

Several investigators have found that the average crack growth rate decreases exponentially with time for initially plain specimens or fatigue-precracked specimens where the precrack does not extend to the edges of the specimen (Parkins 1987; Parkins and Zhou 1997; Parkins, Belhimer, and Blanchard 1993; Baker, Rochfort, and Parkins 1986; Marshall 1984). A typical behavior pattern is illustrated in Figure A-11, where the slope of the line usually is between -0.8 and -1.0. A slope of -1.0 would indicate zero growth, and a crack characterized by a slope of -0.9 would be less than 0.1 mm deep in 100 years. Thus, the measured crack growth rates in the laboratory become negligibly small in a few days.

One possible explanation for how cracks that move so rapidly toward dormancy can eventually grow large enough to cause a service failure in a pipeline has been given by Leis (Leis and Parkins 1993) who monitored the lengths of cracks on the surface of a specimen

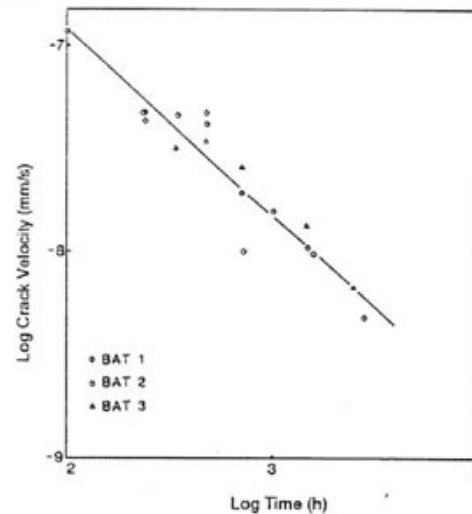


Figure A-13-11 Effect of Time on Average Velocity of a Single High pH Stress-Corrosion Crack

exposed to the carbonate/bicarbonate solution. As is shown in Figure A-12, crack growth stopped and restarted a number of times during the experiment. The periodic halting of the crack was attributed to creep exhaustion, and the restarting was attributed to coalescence of a dormant crack with other cracks that had initiated near the ends of the first crack. It has been demonstrated that cracks continue to nucleate as time goes on (Parkins 1988). Computer simulations of crack growth were carried out for five different initial random distributions of cracks assuming the exponential decreases in growth rate and nucleation rate with time but allowing for crack coalescence whenever

the separations were less than 14 percent of the average lengths (Leis and Parkins 1993). The results, shown in Figure A-13, compare remarkably well with the measurements shown in Figure A-12. The dashed line in Figure A-13 represents the crack growth that would be expected in the absence of coalescence.

Leis, et al. have developed a quantitative crack growth model for high pH SCC (Leis, Forte, and Ghadiali 1995) that reproduces the general features of Stages 2, 3, and 4 in Parkins' model. Called SCCLPM (stress-corrosion-cracking life-prediction model), it involves the following steps:

1. Generating a random array of cracks where the cracks depths and number of cracks per unit area are functions of the stress on the pipe, the yield strength of the steel, and the proportional limit of the steel, the relationships being determined from laboratory tests.
2. Updating the nucleated array of cracks to account for additional crack nucleation near the ends of the first cracks due to the increased stress concentration there.
3. Allowing the cracks to grow according to some kinetic relationship. This is the only part of the model that is specific to

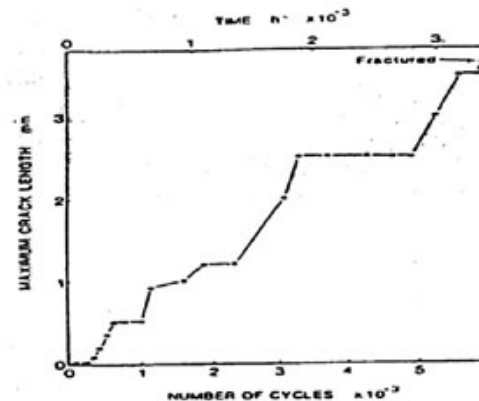


Figure A-13-12 Intermittent Growth of High pH Stress-Corrosion Cracks

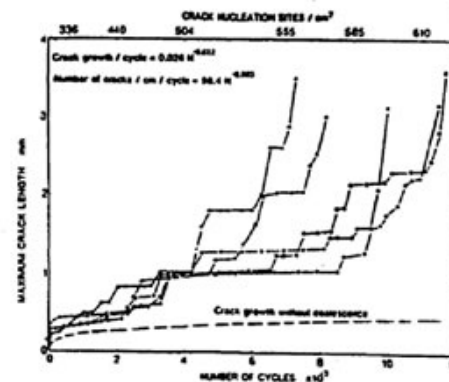


Figure A-13-13 Simulated Growth of High pH Stress-Corrosion Cracks Showing Intermittent Growth Due to Crack Coalescence

high pH SCC. It uses the crack growth rate predicted by Faraday's Law whenever the steel is experiencing a strain rate sufficient to support SCC. The strain rate depends upon the cyclic stresses and the mean stress, and it decreases over time due to work hardening. Continued crack growth depends upon crack coalescence. The effects of cyclic softening can be included in the model for a specific steel, but they have not been included in a generic sense. As Leis points out, it would be desirable to do so.

4. The cracks are allowed to grow until they, as a group within the cluster, reach a critical size for mechanical extension by tearing.

The model is pipeline specific with respect to size, grade, toughness, service conditions, and hydrostatic-test history.

Predictions from the model have been compared with the behavior of an actual operating pipeline that contained SCC. The predictions agreed well with the aspect ratio, time to failure, crack depth, and relative incidence of dense to sparse cracking (Leis 1997). The model also can predict dormancy and re-initiation of cracks. It predicted that reductions in pressure cycling and discharge temperature were the most important parameters to extend the service life of pipelines suffering high pH SCC.

A more complicated probabilistic model had been formulated based upon the deterministic model SCCLPM but considering random variations or uncertainties in mechanical properties of the pipe, gas pressure, temperature, and electrochemical potential (Leis and Kurth 1999). This model has been used to quantify the beneficial effects of lowering discharge temperatures and to develop guidelines for optimizing hydrostatic-retest procedures. Those results will be described in more detail later in this document.

Models of Near-neutral pH SCC Growth Kinetics. A variety of possible initiation mechanisms for near-neutral pH SCC have been proposed by several investigators. (Parkins and Delanty 1996; King, et al., 2001) For the most part, crack-like features that were produced at the surface failed to extend more than 0.02 mm below the surface and did not closely resemble typical deep stress-corrosion cracks. Currently, there is no well-accepted model for initiation of near-neutral pH SCC.

In laboratory bend tests with specimens from the field that contained service-induced stress-corrosion cracks, only 8.5 percent of the cracks could be activated, and 80 percent of the growing cracks were near the edges of the clusters (Jack et al. 1994).

Beavers and Jaske (2002) measured instantaneous crack growth rates with an electric-potential-drop technique and found that crack velocities decreased continuously after the start of a test with low-frequency, high-R stress fluctuations typical of those on a gas pipeline. As is shown in Figure A-14, higher-frequency, lower-R fluctuations, which probably caused corrosion fatigue, resulted in increasing crack velocities. Decreasing crack velocities with time also have been observed by Parkins, (2002) as is shown in Figure A-15, where the slopes of the lines are between -0.8 and -0.9, indicating that crack growth had almost stopped by the end of the tests.

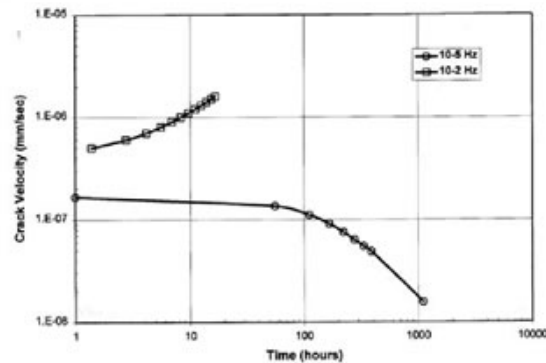


Figure A-13-14 Variations of Crack Velocity with Time for Near-Neutral pH SCC

Chudnovsky (Zhang et al. 2000) has attempted to develop a thermodynamic model for the growth of near-neutral pH stress-corrosion cracks. The approach starts with a sophisticated mathematical formalism that ultimately depends upon laboratory experiments to determine key parameters such as the electro-chemical driving force. Those parameters are in question because they were determined under conditions of high-frequency, low-R stress fluctuations and cathodic charging. Thus it is more likely that he was producing data for corrosion fatigue rather than stress-corrosion cracking. Other problems with his approach are that it does not consider decreasing crack velocity with time, the importance of plastic strain as opposed to stress intensity, and kinetic considerations such as diffusion in the liquid or in the steel.

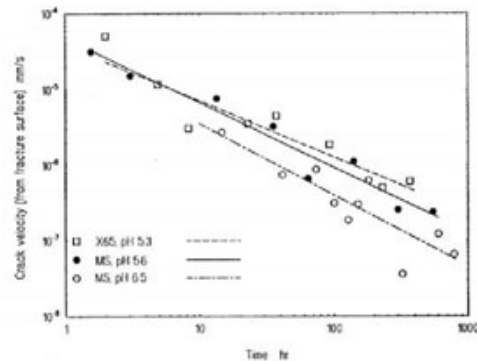


Figure A-13-15 Decrease in Average Crack Velocity with Time for Near-Neutral pH SCC

Krishnamurthy, et al. (1996) used an elastic-plastic (J-integral) analysis to calculate the safe remaining life of pipe with near-neutral pH stress-corrosion cracks of known depths. Results of their calculations are shown in Figure A-16 for predicted remaining life of a pipe with different size cracks and recommended hydrostatic-retest frequency as a function of retest pressure and maximum operating pressure. The results probably are somewhat conservative because the calculations

involved two conservative assumptions: (1) that the cracks were infinitely long, and (2) that crack velocity as a function of J could be extrapolated from some tests by Harle, et al., (1994) which were conducted with very aggressive stressing conditions, conditions that produced substantial crack growth even in the absence of a liquid environment. Nevertheless, the model allows the company to make justifiable decisions about operating the pipeline and scheduling remedial measures. It also provides an interesting framework that could be refined to make it less conservative.

For pipelines that experience both high-frequency, low-R stress fluctuations and low-frequency, high-R fluctuations, Lambert and others (Lambert et al. 2000) have proposed a superposition model, where the amount of corrosion-fatigue crack growth from the low-R fluctuations is simply added to the amount of stress-corrosion crack growth from the high-R fluctuations. While that approach seems reasonable, plots of the data, as shown in Figure A-17, contain so much scatter that it is difficult to judge the quality of agreement between experiment and theory. Part of the problem might stem from the fact that they do not consider variations of the rate of SCC with time.

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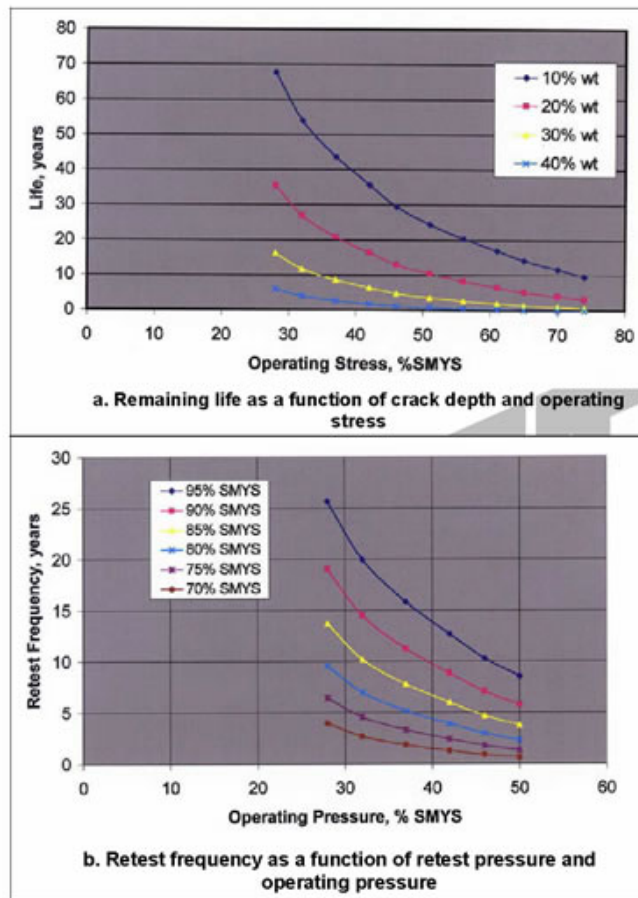


Figure A-13-16 Results of Elastic-Plastic Analysis for a Specific Liquid Pipeline with Near-Neutral pH SCC

(Note: These results are pipeline specific; they do not apply to any pipeline in general.)

In fact, none of the models for near-neutral pH SCC that have been proposed to date consider or predict the decrease in crack growth rate with time.

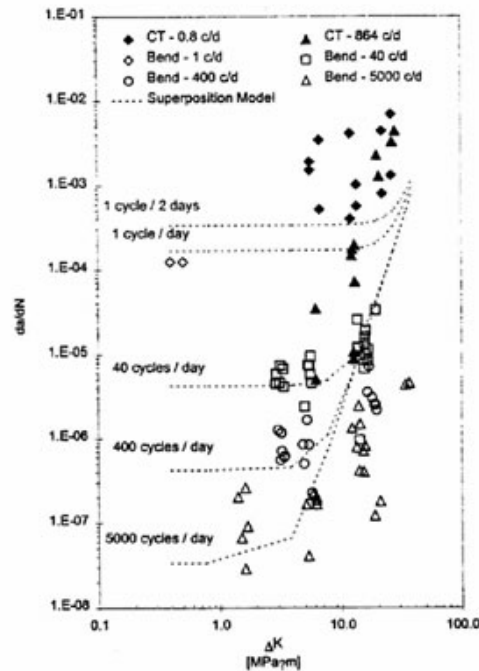


Figure A-13-17 Crack-Growth Data Generated in a Near-Neutral pH Environment

Gaps Related to Crack-Growth Models. Determining how frequently to test requires reliable crack growth models. The advantages and disadvantages of current models have been discussed above. Leis (Leis and Kurth 1999) used his probabilistic life-prediction model to calculate that the time to the first retest could vary from 10 to 70 years depending upon the aggressiveness of the environment and the operating conditions. Subsequent retest intervals could vary from 3 to 30 years depending upon those same parameters plus the previous retest pressure. The calculations must be customized to each pipeline. Refining the model to make it more user friendly would help in this matter. The above calculations were for high pH SCC, but a comparable interval for near-neutral pH SCC in “highly susceptible valve sections” of 2 to 3 years was determined from observations of crack growth following a hydrostatic retest (Delanty and O’Beirne 1992). A model to predict the effects of operating pressure and retest pressure on retest frequency has been discussed with reference to Figure A-16.

Crack-growth models also are useful for determining optimum pressures and hold times. Using his probabilistic life-prediction model, Leis showed that retesting to 95 percent of the specified minimum yield strength (SMYS) or below produces almost no benefit in terms of increasing remaining life, but higher retest pressures can be very beneficial. Pressures between 105 and 110

percent SMYS for 1 hour followed by a longer, lower-pressure leak test appeared to be optimum. A totally independent model for near-neutral pH SCC also shows a pronounced effect of retest pressure and demonstrates the need to exceed 95 percent SMYS if future operating stresses are going to exceed 50 to 60 percent SMYS (see Figure A-16). It is difficult to see how additional research would add to our knowledge in this area.

There are a number of significant challenges to developing a quantitative model for the kinetics of crack growth for either high pH or near-neutral pH SCC. The first is the inability to calculate the length of Stage I, the time required to establish the necessary environmental conditions at the surface of the steel. That is, in fact, just a subset of the larger problem of not having specific knowledge about the severity of the environmental conditions anywhere along the pipe.

Another challenge is modeling the acceleration or re-initiation of a crack that is moving rapidly toward dormancy. Several possible mechanisms have been suggested:

1. Crack coalescence, which has been discussed above.
2. Re-initiation of creep strain due to softening as the result of continued cyclic loading. Figure A-13-18 shows an example of this, (Leis and Parkins 1993) where creep essentially stopped after about 400 cycles but then resumed after about 1000 cycles.
3. Re-initiation of creep due to a single large stress cycle, such as complete unloading and reloading. Figure A-13-19 shows an example of that phenomenon (Leis and Parkins 1993) and Figure A-20 shows how such unloading and reloading can result in bursts of additional crack growth (Beavers and Jaske 2002).

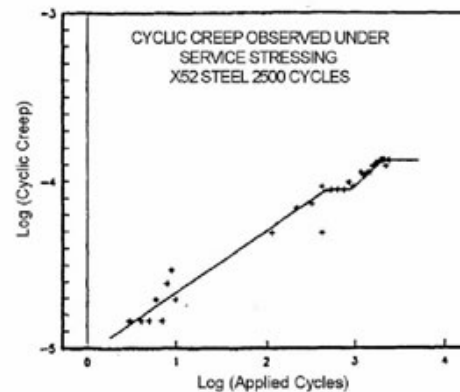


Figure A-13-18 Creep Exhaustion Followed by Re-Initiation of Creep Due to Additional Stress Cycles

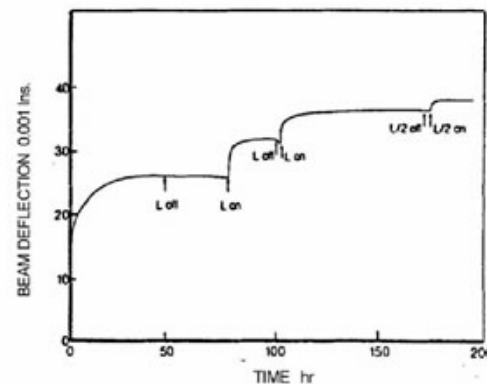


Figure A-13-19 Creep Exhaustion Followed by Re-Initiation of Creep Due to Loading and Unloading

The first of those mechanisms is considered in Leis's SCCLPM; all three may be important for operating pipelines.

Leis's probabilistic model for high pH SCC is the most sophisticated and complete, but its complexity is a discouragement to wide-spread use. It might be more useful if its results could be illustrated in charts or tables for typical operating conditions. Also, as the Leis has suggested, it should be expanded to include the effects of cyclic softening.

That same model might also be appropriate for near-neutral pH SCC if the appropriate growth mechanism for a single crack were better understood.

In spite of all the difficulties, by making reasonable but conservative estimates about some of the unknown parameters, existing models have provided useful insight and guidance to pipeline companies.

Possible improvements to existing crack growth models include the following:

- Incorporate the effects of cyclic softening and high-amplitude stress cycles into SCCLPM and the probabilistic model for high pH SCC.
- Use the probabilistic model to investigate reasonable ranges of the important parameters and present the results in tables or charts that can provide the basis for at least "rule-of-thumb" guidelines to pipeline operators.
- Expand SCCLPM and the probabilistic model to cover near-neutral pH SCC.

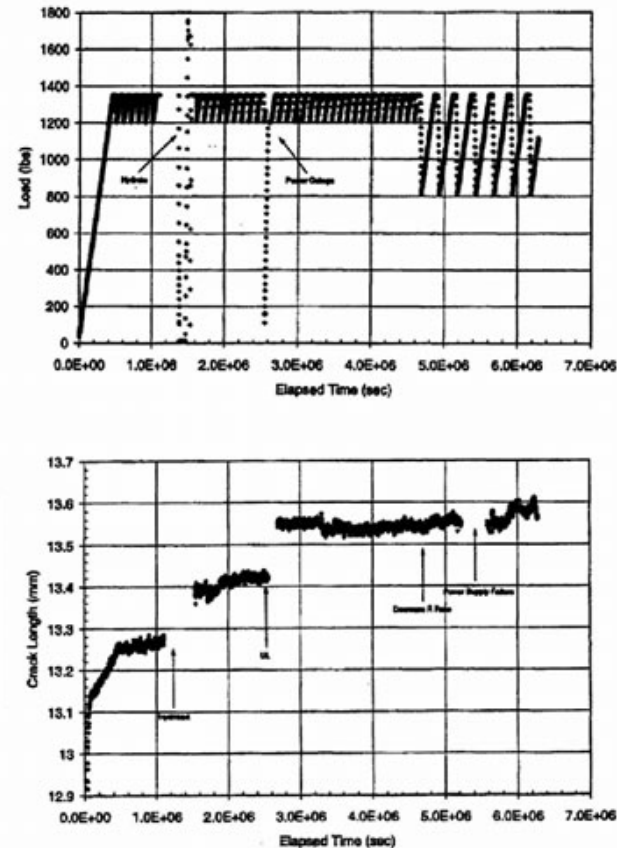


Figure A-13-20 Bursts of Crack Growth (Lower Graph) Due to Unloading and Reloading (Upper Graph)

- Incorporate more realistic crack growth rates into the elastic-plastic model for near-neutral pH SCC.
- Expand the elastic-plastic model to cover high pH SCC.
- Compare the predictions from SCCLPM and the probabilistic model with those from the elastic-plastic model.

A.3.3 *ILI Technologies*

ILI technologies for detecting, characterizing, and sizing stress-corrosion cracks in pipelines are described in Section 6.2.2 of this document. ILI obviously is important in locating SCC and offers an attractive substitute for hydrostatic retesting in some situations. In principle, ILI can provide much more information, especially about locations and sizes of cracks or crack clusters that are too small to cause a failure during a hydrostatic test. ILI also is important for risk assessment.

ILI crack-detection tools have been built based upon liquid-coupled ultrasonics, wheel-coupled ultrasonics, magnetic-flux leakage, and electromagnetic acoustic transducers (EMAT). The only technology that has been satisfactory in terms of locating, identifying, and sizing cracks is liquid-coupled ultrasonics. Unfortunately, it is very difficult (many would say impractical) to use in gas pipelines because it requires surrounding the tool with a slug of water. Procedures to do so may be more trouble than conducting a hydrostatic retest. Considerable hope has been placed on the development of a new technology based upon EMAT that does not require the pipe to be filled with a liquid. At least two vendors are developing such a tool, and they will need pipeline companies to provide manpower, equipment, and pipelines to evaluate them in their final stages of development.

The highly competitive, proprietary nature of the ILI industry makes it difficult for public organizations to participate in developing new technologies or tools. The vendors seem willing to do so if the pipeline companies will commit to using the tools once they are developed and shown to be reliable and durable. The industry should stimulate the academic and/or basic-research community to suggest new technologies that might be overlooked by the ILI vendors.

A.3.4 *In-the-Ditch Sizing*

In principle, it should be much easier to size cracks in the ditch than from an ILI tool moving down the pipe. However, in a recent critical evaluation of ten technologies, “none of the measurement technologies completely met the goal of simple, low cost, operator-independent crack sizing.” (Francini et al. 2000) Ultrasonic techniques appeared to have the most promise. Electromagnetic methods consistently underestimated the sizes of the stress-corrosion cracks. New, innovative approaches should be pursued.

A.3.5 *Effect of Temperature*

The effect of temperature is a part of crack-growth modeling. The effect on high pH SCC is well known, and additional research in this area probably would have little benefit. The effect for near-neutral pH SCC is not so clearly established, but it does not appear to be a major factor.

A.3.6 Steel Susceptibility

Some people in the industry are convinced that enough is known about the beneficial effects of surface treatments (shot or grit blasting) and certain types of coatings that future pipelines can be designed to be safe from SCC regardless of the inherent susceptibility of the steel. Others prefer a “belt-and-suspenders” approach for cases where the coating is damaged or deteriorates in service.

Susceptibility to High pH SCC. Because high pH SCC involves selective dissolution at grain boundaries, a number of researchers have looked for chemical segregation to the grain boundaries to explain why they are more susceptible to corrosion. Based upon past work with other kinds of steels in other environments, the principal suspects were sulfur, phosphorus, and carbon. Danielson, et al. (2000) tried to produce intergranular fractures in pipe-steel specimens while they were in an Auger spectrometer to analyze the compositions at grain boundaries, but they were unable to produce intergranular fractures. Wang, et al. (2001) used electron energy-loss spectroscopy in a high-resolution analytical electron microscope to look at cross-sections through grain boundaries, and they were unable to detect any segregation of S, P, or C in samples of X42, X52, and X65 steel. Hunt (1988) prepared a number of steels with various levels of P, S, Cu, Sn, and Ni and compared their susceptibilities to high pH SCC by comparing times to failure in slow-strain-rate tests. Although he was able to detect phosphorous segregation to some of the grain boundaries, he found longer failure times (implying lower susceptibilities) for all of the steels with added impurities.

Also using slow-strain-rate tests, Parkins, et al. (1981) studied the effects of Mo, Cr, Ni, and Ti additions. Under these test conditions, it required unacceptably large additions (e.g., 1 percent titanium) to impart high resistance to high pH SCC. However, any improvement to the creep resistance of the steels would not have been detected in those tests.

Using tapered-tensile-specimen tests with superimposed, high-R, cyclic loads to measure the threshold stresses of six line-pipe steels ranging from Grade X42 to X70, Wells (1993) found no correlation between susceptibility (as measured by the ratio of threshold stress to SMYS or actual yield strength) and pipe grade. Using a similar approach with two X70 steels and an X80 steel, Christman (1988a) measured threshold stresses between 42 and 60 ksi, and the susceptibility decreased somewhat with increasing yield strength and grade. The susceptibility was judged to be comparable to, or better than, that of many X52 steels.

In sharp contrast to those results, Danielson, et al., (2001) using precracked, compact-tension specimens, found the critical stress-intensity (K_{Isc}) for three randomly selected heats of X65, X70, and X80 steels to be at least 20 percent lower than those of six heats of older X52 steel. The heats of X52 steel were selected to have as broad a range of compositions as possible so as to produce a range of susceptibilities, but all six had comparable critical stress-intensity factors and crack growth rates.

Asahi, et al., (1996) measured the threshold stress of five different steels that were processed differently to produce different microstructures. The steels included an X80 and X65 steel that were thermomechanically controlled processed (TMCP), an X65 steel that was quenched and tempered (QT), and an X65 steel and X52 steel that were controlled rolled (CR). Results of threshold-stress measurements from four different laboratories are shown in Figure A-21. The authors concluded that the TMCP and QT steels, which had more uniform microstructures, were less susceptible to high pH

SCC than were the other two steels. In view of the lack of large differences among the steels, lab-to-lab variations for a single steel, and the limited number of steels in the study, a general conclusion about the effect of microstructure would be questionable.

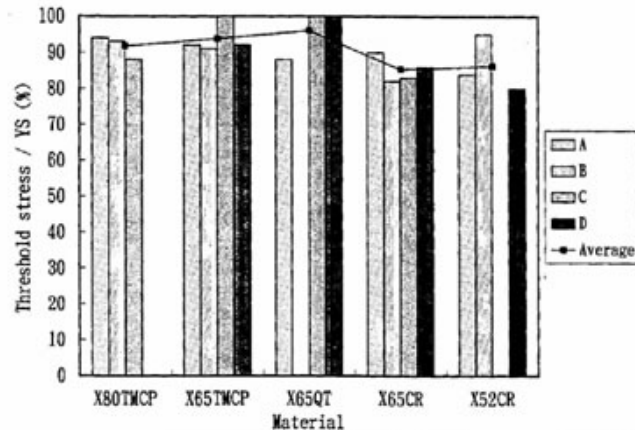


Figure A-13-21 Susceptibilities of Five Steels to High pH SCC as Measured in Four Laboratories (Designated A Through D in the legend)

For any given steel, small amounts of plastic strain, on the order of that which would be produced by forming and cold expanding a pipe, can have a large effect on the threshold stress. Examples for four steels are shown in Figure A-22, where it also can be seen that there is no consistent trend with grade (Fessler and Barlo 1984). Subsequent heating of the type that might be experienced in a coating operation also can affect the threshold stress, as is illustrated in Figure A-23 (Barlo 1979). It is interesting that the coating temperatures for fusion-bonded epoxy, which has not been associated with SCC, produces a much higher threshold stress than does the coating temperature for coal tar, with which most of the high pH SCC failures have been associated.